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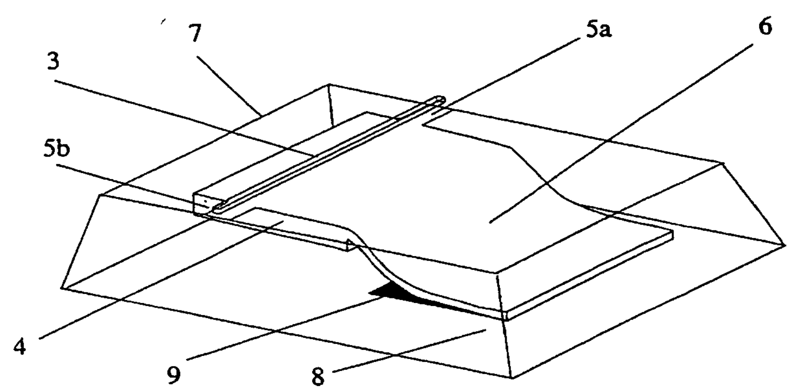
(54) Title: AN INTEGRATED PLANAR WAVEGUIDE, AND A METHOD OF MANUFACTURING IT



WO 00/73838 A1

(57) Abstract: In an integrated optical waveguide and a method of manufacturing it, a section for changing polarization state is formed as an independent rotatable unit. The rotation is performed by arranging the independent section on an actuator mechanism consisting of a flap with a sheet (4) on whose upper side the section is arranged. The integrated optical waveguide is formed of a silicon substrate (7) so that the flap is freely movable. The underside of the flap (6) forms an electrode which co-operates with a gold electrode formed on a glass substrate (8), said electrodes constituting the movable parts of the actuator mechanism itself. When a voltage is applied between the electrodes, the integrated optical waveguide will rotate about the axis which is drawn by the direction of light propagation. In an embodiment, the integrated optical waveguide has several sections. The invention provides a polarization controller allowing desired polarization states to be controlled in an optical waveguide, such as in an optical fibre. Also provided is an integrated compensator for use for first order compensation of polarization mode dispersion (PMD) in a wavelength division multiplexing system (WDM).

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An integrated planar waveguide, and a method of manufacturing it

The invention relates to an integrated planar waveguide for transmitting electromagnetic radiation, wherein the light is propagated in the longitudinal direction of the planar optical waveguide, and comprising a section for changing polarization state.

The invention moreover relates to a method of manufacturing an integrated planar waveguide for transmitting electromagnetic radiation and comprising a section for changing polarization state.

Optical planar waveguides for changing the polarization state of light are well-known. These are produced e.g. by affecting the material of which the waveguide is made by electrical or magnetic fields. This is possible only for crystalline materials. Other methods use acoustic or thermal signals which act through the photoelastic effect. Here, crystalline as well as amorphous materials may be used.

The anisotropic effects that can be achieved in the above-mentioned elements by using external signals are modest, and relatively long extents are therefore required to achieve effective interaction between the external field and the light in the guide. Typically, 10 mm - 20 mm waveguides are required.

The object of the invention is to make it possible to achieve a controlled interaction between the light and a strongly anisotropically designed waveguide, allowing a complete change in the polarization state to be achieved.

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The object of the invention is achieved in that the section for changing polarization state is independently rotatable about the direction of light propagation relatively to the waveguide in general. It should be mentioned in this connection that typically at least two 50 - 100 μm long sections are required to achieve the complete change in the polarization state.

As stated in claim 2, the rotatable waveguide may be formed such that at least two different directions of polarization exhibit different longitudinal coefficients of propagation. This may e.g. be done by forming the waveguide with a rectangular cross-section, there being a difference between the longitudinal coefficients of propagation of the TE and TM wave types. A great difference in the longitudinal coefficients of propagation may also be achieved by introducing thin layers of material with a high index of refraction on one or two opposite sides of a waveguide of rectangular or square cross-section. Another possibility is to place a thin high index layer in the centre of waveguide core. In these cases, the thin layers give rise to internal stress in the structure. This stress occurs because of the difference in thermal coefficients of expansion of the thin layers and the surrounding glass.

As stated in claim 3, the rotatable waveguide may be formed such as to allow transmission of only one direction of polarization. This may e.g. be embodied by applying a metal layer or other absorbing material to one of the cross-sectional sides of the waveguide. Hereby, the polarization state oscillating in the plane to which the absorbing layer is applied, will not be affected by it,

while the state oscillating orthogonal to the absorbing layer will be attenuated. The absorbing layer may e.g. be applied to the rotatable section by a lift-off technique.

For performing the rotations of the optical waveguide according to the invention, it is expedient if, as stated in claim 4, it is arranged on an actuator mechanism, and additionally, as stated in claim 5, that the actuator mechanism consists of at least one flap with a sheet on whose upper side the section for changing polarization state is mounted.

It is stated in claim 6 that the flap is formed as an electrode which is provided with an insulating film on its underside, and which, together with a gold electrode on a glass substrate, causes the flap to move.

Expediently, as stated in claim 7, the flap is formed in a silicon substrate. For suitable background doping, this will exhibit electrical conductivity and may hereby be used directly as an electrode.

For use in the application of the optical waveguide according to the invention when switching from one random polarization state to another random polarization state, it is an advantage if, as stated in claim 8, the waveguide contains several sections which may be rotated individually. This may e.g. be for a single compensator, where at least two sections are arranged in series along an axis which is parallel with the direction of light propagation. For use in the application of the optical waveguide according to the invention for compensating the polarization mode dispersion (PMD), it is an advantage to arrange several sections which may be rotated individu-

ally, in parallel between a wavelength demultiplexer and a wavelength multiplexer. Hereby, the individual wavelength channels in a wavelength division multiplexing signal (WDM) may be corrected individually.

For use as an optical insulator, it is expedient, as stated in claim 9, that at least two sections are rotated 45° relatively to each other about a common axis defined by the direction of light propagation.

Expedient embodiments of the optical waveguide are defined in the dependent claims in general.

As mentioned, the invention also relates to a method.

This method is defined in claim 10 and is characterized by comprising the steps of:

a) forming on a silicon substrate an optical waveguide consisting of a core surrounded by a glass cladding,

b) applying a mask to the rear side of the silicon substrate and etching a silicon sheet out of a part of the substrate which is disposed below the optical waveguide,

c) applying a further mask to the rear side of the silicon substrate and etching at least one flap out of a part of the substrate which is disposed in extension of the silicon sheet,

d) applying a mask to the front side of the silicon substrate and then releasing the silicon sheet and the flap,

e) applying an insulating film to the flap,

f) applying to a glass substrate a metal pattern which forms an electrode,

g) joining the silicon substrate with the glass substrate so that the free end of the flap is joined with the glass substrate.

Expedient embodiments of the method according to the invention are defined in claims 11 and 12.

In a simple embodiment of the invention, the actual rotation of the waveguide section is achieved by twisting the waveguide cross-section in the transition between sheet and substrate. Such a structure will require a relatively long transitional member between substrate and sheet to allow significant rotation of the member without causing ruptures in it. To achieve considerably shorter transitional members for the section, claim 11 provides an expedient method of manufacturing a rotary bearing for the structure. This rotary bearing is manufactured by replacing item a) in the method defined in claim 10 by a method comprising the steps of:

a1) applying a lower glass cladding and a first glass core to the front side of the substrate,

a2) applying a mask to the front side of the substrate and forming a part of the core by an etch,

a3) applying a sacrificial layer to the front side of the substrate,

a4) applying a second mask to the front side of the substrate and removing a part of the sacrificial layer by an etch,

a5) applying a second glass core to the front side,

a6) applying a third mask to the front side of the substrate and forming the last part of the core by an etch,

a7) heat-treating the glass core,

a8) applying a further sacrificial layer to the front side,

a9) applying a fourth mask to the front side and removing excess sacrificial layer by an etch,

a10) applying an upper glass cladding to the front side of the substrate.

These rotary bearings are released during the etching in step d) when sheet and flap are released.

In an expedient embodiment, as defined in claim 12, the sacrificial layer is formed in amorphous or polycrystalline silicon or in silicon nitride. The requirement to be met by the sacrificial layer is that it must be capable of resisting the etch of glass core and cladding, while being removable without the glass core and cladding being etched.

The invention will now be explained more fully with reference to an example shown in the drawing, in which

fig. 1 schematically shows the basic principle of the invention,

fig. 2 shows the structure of a component with a planar optical waveguide with controllable rotation,

fig. 3 is a cross-sectional view of the component of fig. 2 in a first working position,

fig. 4 shows the component of fig. 3 in a second working position, and

figs 5a) - 5f) show the method of manufacturing a rotary bearing.

In fig. 1, 1a, 1b designate planar waveguides which have a common axis along which the light propagates. A section 2 is interposed between the two planar waveguides, intended for changing the polarization state, which may e.g. be the direction of polarization of a wave (not shown) from the left-hand side of the figure in the planar waveguide 1a to the planar waveguide 1b shown at the right-hand side of the figure, or vice versa.

In an expedient embodiment of the invention, the section 2 is separated from the planar waveguides 1a, 1b and can thus rotate about its axis, without the planar waveguides being affected by physical forces. The method of manufacturing rotary bearings for such a structure will be explained more fully in connection with fig. 5.

In a simpler embodiment, two transitional members will be provided between the section 2 and the planar waveguides 1a and 1b. These transitional members, designated 5a and 5b in fig. 2, are subjected to a twisting which does not give rise to any significant double refraction and is thus without importance to the optical function of the component. These transitional members, however, are of importance in connection with the size of the component.

As is generally known, the section 2 may be designed with a polarizing or double-refracting effect. In general, as is also well-known, the section has a core which is surrounded by a cladding. The principle of waveguide effect may be total internal reflection or reflection against a photonic crystal structure. The size of the core may be dimensioned for both single mode and multimode wave propagation.

In fig. 2, the section 2 is shown as a double-refracting section 3 with a core which has a rectangular cross-section and is incorporated in a rotating mechanism, as will be explained more fully below, cf. also figs. 3 and 4, where, however, the section 3 is shown with a core of square cross-section.

On a silicon substrate 7, an optical waveguide of glass is formed with a core 11 and a cladding 10. A mask is applied to the opposite side of the silicon substrate 7, and then a sheet 4 is provided by etching.

Then, a further mask covering the sheet is applied, following which a flap 6 is provided in extension of the sheet 4 by etching.

Still a further mask is applied to the front side of the silicon substrate, and etching is carried out, following which the entire sheet 4 and parts of the flap 6 are released from the silicon substrate, as shown at 12 and 13 in fig. 3. An insulating film is applied to the underside of the flap, which may be done e.g. by a thermal oxidation of the silicon substrate.

An electrode part, preferably of gold 9, is deposited on a glass substrate 8.

Finally, the silicon substrate 7 and the glass substrate 8 are joined at the locations shown by the reference numerals 14, 15 and 16 in fig. 3.

The manufacture of a rotary bearing will be described below with reference to figs. 5a) - 5f). This method introduces a rotary bearing in the waveguide from the above method.

In fig. 5a), a lower glass cladding 20 and a first glass core 21 are applied to the front side of the substrate. A mask is applied to the front side of the substrate, and a part of the core is formed by an etch 22. A sacrificial layer is applied to the front side of the substrate 23, and a second mask is applied to the front side of the substrate, and a part of the sacrificial layer is removed by an etch. A second glass core is applied to the front side, and a third mask is applied to the front side, following which the last part of the core is formed by an etch 24. The glass core is heat treated to achieve a rounded profile for the rotary member, following which another sacrificial layer is applied to the front side 25. A fourth mask is applied to the front side, and

excess sacrifice layer is removed by an etch. An upper glass cladding is applied to the front side of the substrate 26. The rotary bearing is released during the same etch as releases the sheet 4 and the flap, as outlined in fig. 5f). Here, sheet and flap are released by a glass etch, which is then followed by an etch of the sacrificial layer. As a result, the rotary bearing consists of a short piece of glass core 24 which is embedded in the glass claddings 20 and 26.

The function of the above-mentioned, manufactured component is as follows:

The effect of applying a voltage to the electrode will be illustrated with the core 11 shown in fig. 3 as the basis. This voltage causes the flap 6 to be attracted by the electrode, whereby the sheet 4 with waveguide core 17 rotates, as shown in fig. 4. It should be stressed in this connection that in the rotation the waveguide with core 11 and cladding 10 maintains the position of its longitudinal axis along which the light propagates. Hereby, the light travelling along the waveguide 11 experiences a changed orientation of the cross-section of the waveguide 17 when the flap 6 is attracted. This gives rise to changed coupling to the TE and TM wave types, respectively, in the waveguide core 17 from the core 11.

<u>Example 1</u>

The use of the section described above, if combined with a plurality of the same sections in series along an axis which is parallel with the direction of light propagation, makes it possible to provide a polarization controller.

In an embodiment of such a controller, two separate half-wave and quarter-wave sections are combined to an integrated system, in which the individual optical axes may be rotated ±45° independently of each other. The rotation of ±45° is achieved by attaching an actuator mechanism to each side of a waveguide section. The advantage of using such a polarization controller is that it is possible to change the direction of polarization and the state of the light with just a very low loss of power.

Another embodiment with a smaller rotation of the optical axes may be achieved by increasing the number of sections, which must alternately exhibit a positive and a negative phase delay and be rotated to the right and to the left, respectively, relatively to the direction of light propagation.

Example 2

A variable analyzer may be manufactured by arranging a polarizer as the rotatable wave guiding section. Rotation of the polarizer produces a variable analyzer.

Example 3

An optical insulator may be manufactured by arranging a quarter-wave section between two polarizers, the axes of these having been rotated 45° mutually.

The optical insulator is manufactured by applying to the first waveguide section a metal layer which attenuates the propagation of the TM wave type, so that just the TE wave type is transmitted through the first section. The TE wave is the linear polarization state which oscillates in the plane of the substrate. The second section is formed so as to give rise to a phase delay of $\pi/2$, and

such that the optical axis is rotated 45° relatively to the plane of the substrate. After the second section, the light will be linearly polarized with a direction rotated 45° relatively to the output of the first section. The axis of the polarizer in the third section has likewise been rotated 45° relatively to the axis of the first section, thereby allowing unobstructed passage of the light through it in the guiding direction.

For light reflected back to the optical insulator in the blocking direction, the course is as follows. Passage of section 3 means that the light is linearly polarized with a rotation of 45° relatively to the plane of the substrate. This light is rotated another 45° by passage through section 2, following which it is linearly polarized in a direction rotated 90° relatively to the plane of the substrate. This corresponds to a pure TM wave. This polarization state is attenuated by passage of the first section, whereby no light passes through section 1 in the blocking direction.

Example 4

An optical modulator may be provided by combining a polarization controller, as described above, with a polarizer. By switching between e.g. the TE wave type and the TM wave type, only the TE wave type will be transmitted through a polarizer with an axis in the TE direction. As a substitute for the polarizer, a polarization-sensitive directional coupler may be used in another embodiment.

A further example of a modulator is two polarizers which are rotated independently to the right and to the left, respectively. Passage of light is allowed when their axes are parallel, while the light is extinguished when their

axes are perpendicular to each other. This modulator may also be used as a variable optical attenuator.

Although the invention has been explained in connection with specific examples and embodiments, nothing prevents further embodiments from being manufactured within the scope defined by the claims.

It might e.g. be an actuator on both sides of a waveguide section, thereby allowing rotation of the section clockwise as well as counterclockwise (e.g. ±45°).

Since the waveguide core is interrupted at the two bearings between the waveguide sections, it will be necessary to add a material which adapts the indices of refraction between the sections such that no reflections occur at these transitions. This material might e.g. be an oil with an index of refraction which corresponds to the index of the glass cladding. Another possibility of suppressing reflections at the rotary bearing is to terminate it with an angled face toward the waveguide or to form the bearing with a tip toward the waveguide.

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P a t e n t   C l a i m s :

1. An integrated planar waveguide for transmitting electromagnetic radiation, wherein the light is propagated in the longitudinal direction of the planar optical waveguide, and comprising a section for changing polarization state, c h a r a c t e r i z e d in that the section for changing polarization state is independently rotatable about the longitudinal direction relatively to the waveguide in general.

2. An integrated optical waveguide according to claim 1, c h a r a c t e r i z e d in that the longitudinal coefficient of propagation is different for at least two polarization states.

3. An integrated optical waveguide according to claim 1, c h a r a c t e r i z e d in that it just transmits one polarization state.

4. An integrated optical waveguide according to claims 1-3, c h a r a c t e r i z e d in that it is arranged on an actuator mechanism.

5. An integrated optical waveguide according to claim 4, c h a r a c t e r i z e d in that the actuator mechanism consists of a flap (6) with a sheet (4) on whose upper side the section for changing polarization state is mounted.

6. An integrated optical waveguide according to claim 5, c h a r a c t e r i z e d in that the flap (6) is formed as an electrode which is provided with an insulating film

on its underside, and which, together with a gold electrode (9) on a glass substrate (8), causes the flap to move.

7. An integrated optical waveguide according to claim 5 or 6, c h a r a c t e r i z e d in that the flap (14) is formed in a silicon substrate (7).

8. An integrated optical waveguide according to any one of claims 1-7, c h a r a c t e r i z e d in that it contains several sections.

9. An integrated optical waveguide according to claim 8, c h a r a c t e r i z e d in that at least two sections are rotated 45° relatively to each other about a common axis defined by the direction of light propagation.

10. A method of manufacturing an integrated planar waveguide for transmitting electromagnetic radiation and comprising a section for changing polarization state, c h a r a c t e r i z e d by comprising the steps of:

a) forming on the front side of a silicon substrate (7) an optical waveguide consisting of a core (11) surrounded by a glass cladding (10),

b) applying a mask to the rear side of the silicon substrate and etching a sheet (4) out of a part of the substrate which is disposed below the optical waveguide,

c) applying a further mask to the rear side of the silicon substrate and etching at least one flap (6)

out of a part of the substrate which is disposed in extension of the silicon sheet,

d) applying a mask to the front side of the silicon substrate and then releasing the silicon substrate (4) and the flap (6),

e) applying an insulating film to the flap (6),

f) applying to a glass substrate (8) a metal pattern which forms an electrode (9),

g) joining the silicon substrate with the glass substrate so that the free end (15) of the flap is joined with the glass substrate.

11. A method according to claim 10, c h a r a c t e r i z e d in that step a) of the method is replaced by the following steps of:

a1) applying a lower glass cladding (20) and a first glass core (21) to the front side of the substrate,

a2) applying a mask to the front side of the substrate and forming a part of the core by an etch (22),

a3) applying a sacrificial layer to the front side of the substrate (23),

a4) applying a second mask to the front side of the substrate and removing a part of the sacrificial layer by an etch,

a5) applying a second glass core to the front side,

a6) applying a third mask to the front side of the substrate and forming the last part of the core by an etch (24),

a7) heat-treating the glass core,

a8) applying a further sacrificial layer to the front side (25),

a9) applying a fourth mask to the front side and removing excess sacrificial layer by an etch,

a10) applying an upper glass cladding to the front side of the substrate (26).

12. A method according to claim 11, c h a r a c t e r i z e d in that the sacrificial layer is formed in amorphous or polycrystalline silicon or silicon nitride.

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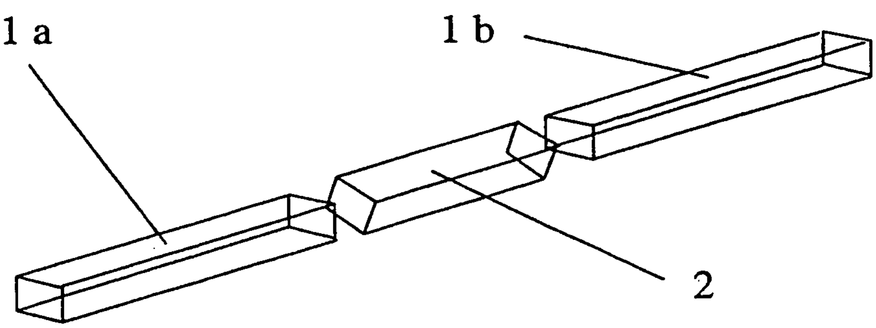

Fig 1

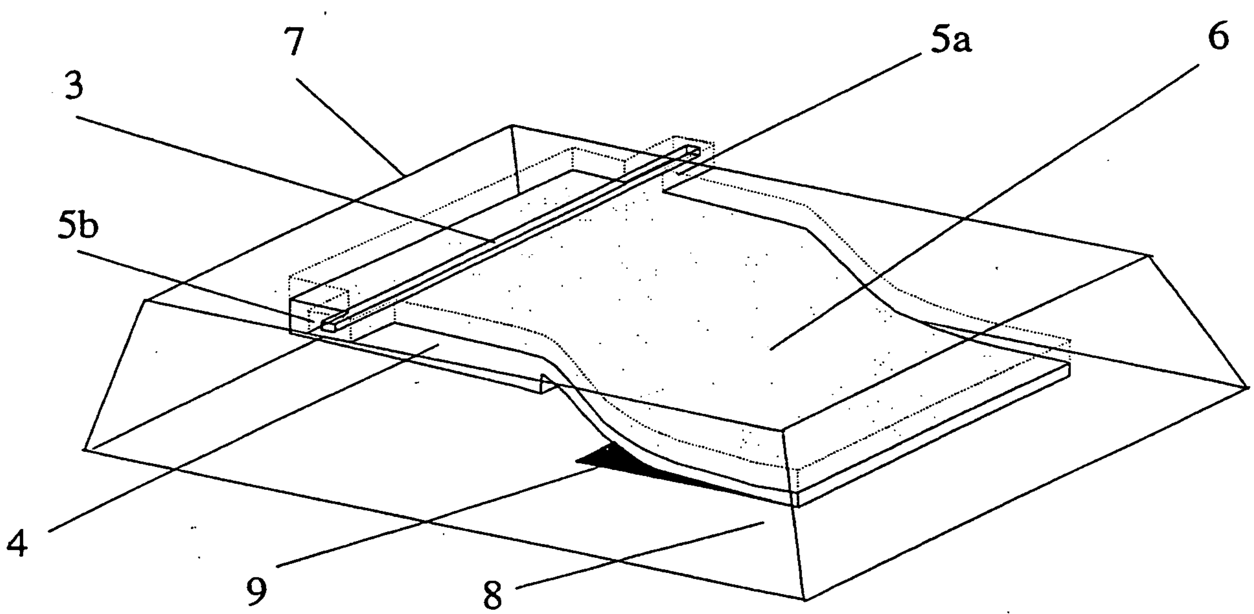

Fig 2

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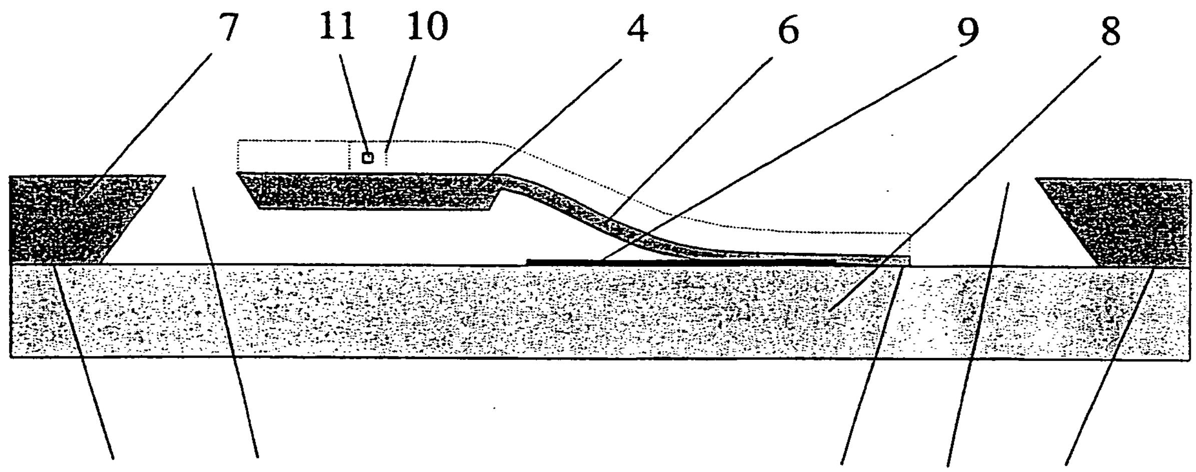

Fig 3

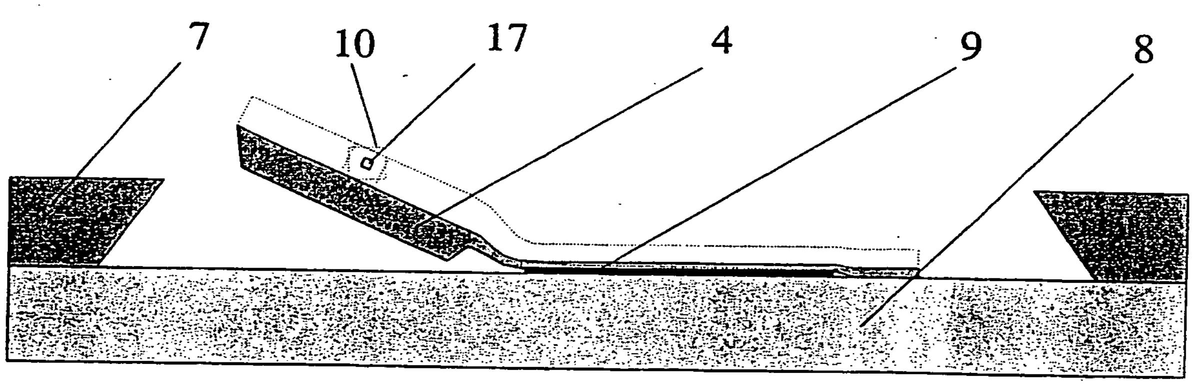

Fig 4

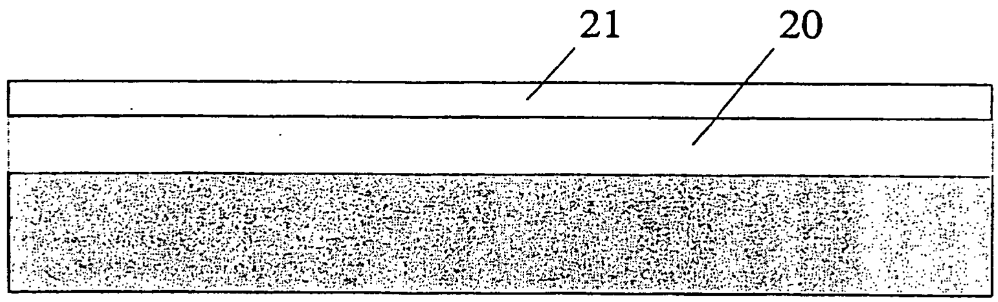

Fig 5a)

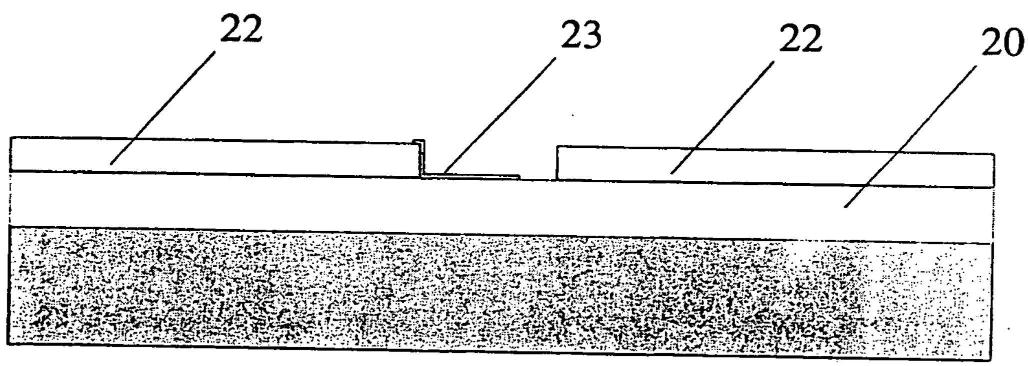

Fig 5b)

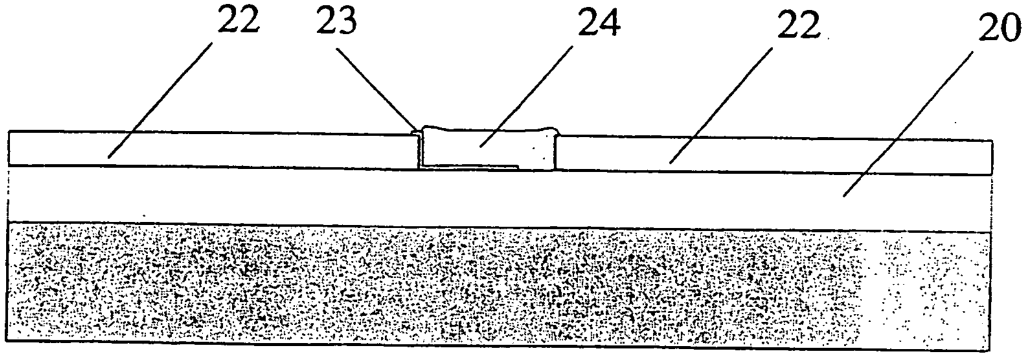

Fig 5c)

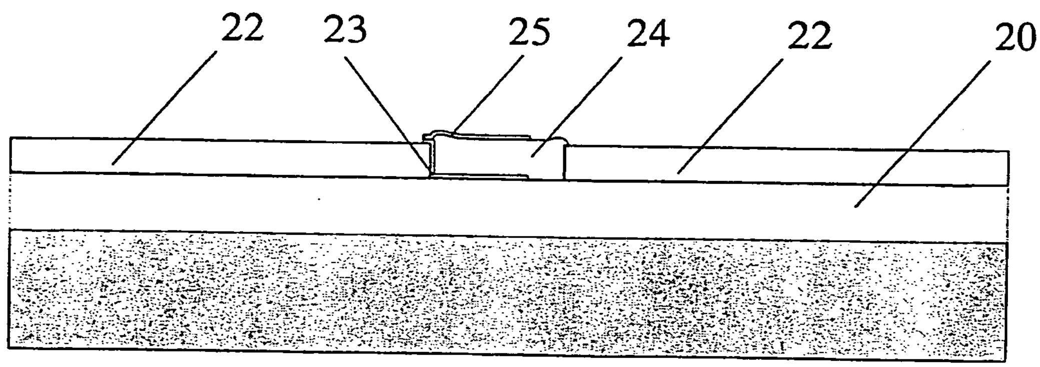

Fig 5d)

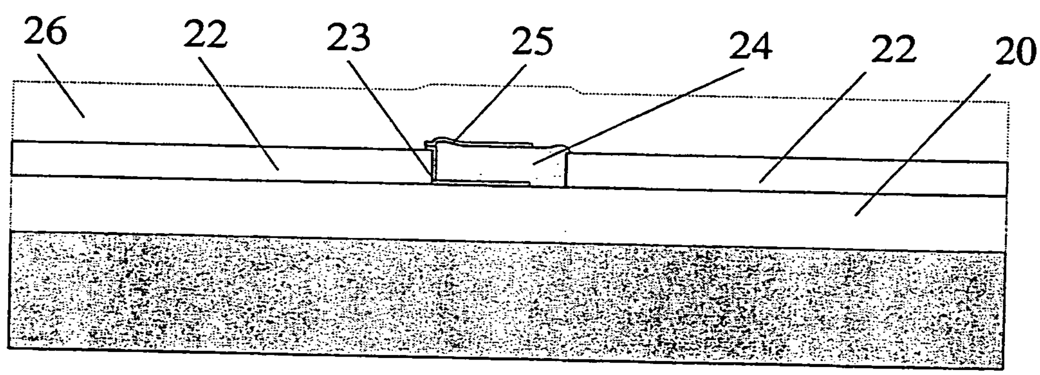

Fig 5e)

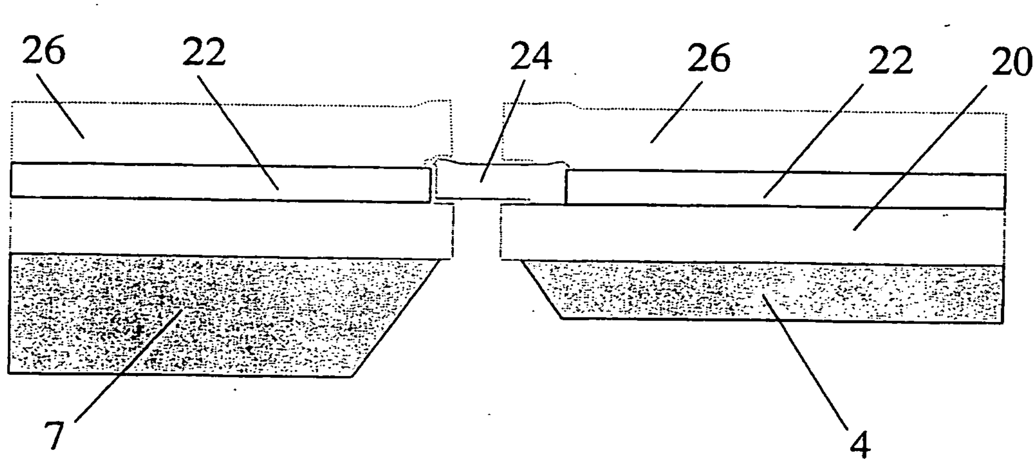

Fig 5f)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/DK 00/00280

A. CLASSIFICATION OF SUBJECT MATTER

IPC7: G02B 26/00, G02B 6/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC7: G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	DE 2443512 A1 (SIEMENS AG), 25 March 1976 (25.03.76) --	1
A	WO 9853352 A1 (DONAM SYSTEMS INC.), 26 November 1998 (26.11.98) -- --------	1

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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Date of the actual completion of the international search	Date of mailing of the international search report
23 August 2000	-9. 10. 2000
Name and mailing address of the International Searching Authority European Patent Office P.B. 5818 Patentlaan 2 NL-2280 HV Rijswijk Tel(+31-70)340-2040, Tx 31 651 epo nl, Fax(+31-70)340-3016	Authorized officer Magnus Westöö/MN Telephone No.

INTERNATIONAL SEARCH REPORT
Information on patent family members

08/05/00

International application No.
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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
DE 2443512 A1	25/03/76	NONE	
WO 9853352 A1	26/11/98	CN 1226972 T	25/08/99
		EP 0920648 A	09/06/99